Integrated Terahertz Heterodyne Focal Plane Array Receivers

Gopal Narayanan, Neal R. Erickson
Five College Radio Astronomy Observatory, University of Massachusetts,
Amherst, MA 01003

Arthur W. Lichtenberger
University of Virginia, Charlottesville

ABSTRACT

The first light heterodyne receivers for SOFIA, and the HIFI heterodyne receiver for Herschel, will be single-pixel receivers, reflecting the technological challenges of building array receivers at these frequencies. The principal technological barrier to space-qualifiable terahertz receivers is the problem of generating adequate local oscillator (LO) power from solid-state frequency multipliers. The first practical monolithic planar frequency multiplier circuits that can provide adequate power for supra-THz heterodyne receivers have recently been demonstrated by our group. We are currently developing integrated heterodyne array receivers by using balanced mixers with direct waveguide-based LO coupling. Such an approach can significantly reduce the amount of LO power required to drive a terahertz focal plane array. A further reduction of the losses in the LO circuit can be achieved by integrating the last stages of the frequency multiplier chain in the array mixer blocks.

In this program we are developing novel, integrated focal plane array receivers for the 1.4 – 1.9 THz frequency band. The final two stages of frequency multiplication will be integrated into the array mixer block, and waveguide power dividers and quadrature networks will be fabricated in-situ in the array block for LO distribution and injection. MMIC-based low-noise IF amplifiers for each pixel will also be integrated next to the mixers.

INTRODUCTION

The relatively unexplored frequency band of 1 – 3 THz in the far-infrared is host to thousands of astrophysically important molecular, atomic and ionic line transitions. The emission from the more important lines such as CII and NII is known to be quite extended[1]. Efficient mapping of such extended sources will require focal plane array receivers. The principal technological barrier to space-qualifiable terahertz receivers is the problem of generating adequate local oscillator (LO) power from solid-state frequency multipliers. While gas lasers have been used to provide LO power for laboratory-class terahertz receivers, they suffer from various problems like limited tunability, and large size and weight, which make them unsuitable for space missions. Given this problem, the first light heterodyne instruments for SOFIA and the HIFI instrument for Herschel have been designed to be single pixel receivers.

What is the technology path to realize adequate LO power to drive future terahertz heterodyne array receivers? Recently, a practical monolithic planar frequency multiplier circuit with good performance at 1.5 THz has been demonstrated[2,3]. This source is expected to be adequate to provide the LO power requirements for a single SIS or HEB mixer, even when used with a weak coupling technique such as a beamsplitter. However, by using balanced mixers with direct waveguide-based LO coupling, we can significantly reduce the amount of LO power required to drive a terahertz focal plane array. At 1.5 THz, waveguide conductive losses can become significant, but if the lengths of high frequency runs are kept small, waveguide coupling of the LO signal is actually less lossy than quasi-optical coupling. A reduction of the losses in the LO circuit can be achieved by integrating the last stages of the frequency multiplier chain in the array mixer blocks.

Contact Information for G. Narayanan: Email: gopal@astro.umass.edu, phone 413 545 0925

In this paper, we present our ongoing research program to develop a novel, 4 × 1 integrated focal plane array receiver for the 1.4 – 1.9 THz frequency band.

INTEGRATED TERAHERTZ ARRAY RECEIVER

Design Philosophy

The main design goal of the instrument under development is to demonstrate a practical technology for space-qualifiable terahertz focal plane array receivers. To achieve this goal, we will utilize several new breakthrough technologies: (1) high efficiency, planar, monolithic Schottky diode frequency multipliers, (2) superconducting hot electron bolometer mixers, and (3) high quality, low cost, integrated waveguide block machined with a novel, high-speed micro-milling machine[4].

We will first describe the overall instrument architecture briefly, and then describe the individual technologies that will be used to fabricate the array in more detail.

System Overview

A block diagram overview of the 4 × 1 array receiver is shown in Figure 1. The entire array with the HEB mixers, planar frequency multipliers, and MMIC IF LNA's will be mounted in a single metal array block which is fabricated using the split-block machining technique.

The LO signal for the 1.4 – 1.9 THz band is generated by two cascaded stages of frequency doublers, which are housed in the array mixer block. The LO input to the array mixer block is through a 350 – 475 GHz waveguide port. The input source power, in turn is derived from multiple stages of active multipliers followed by a W-band power amplifier, followed by two cascaded doublers to produce ~ 10 mW of power at 400 GHz. An in-phase waveguide power divider splits the 350 – 475 GHz LO source power into two branches. In each branch, there are two cascaded frequency doublers, which results in an output LO frequency band of 1.4 – 1.9 THz. Another in-phase waveguide power divider splits the final stage of the LO to feed two adjacent pixels.

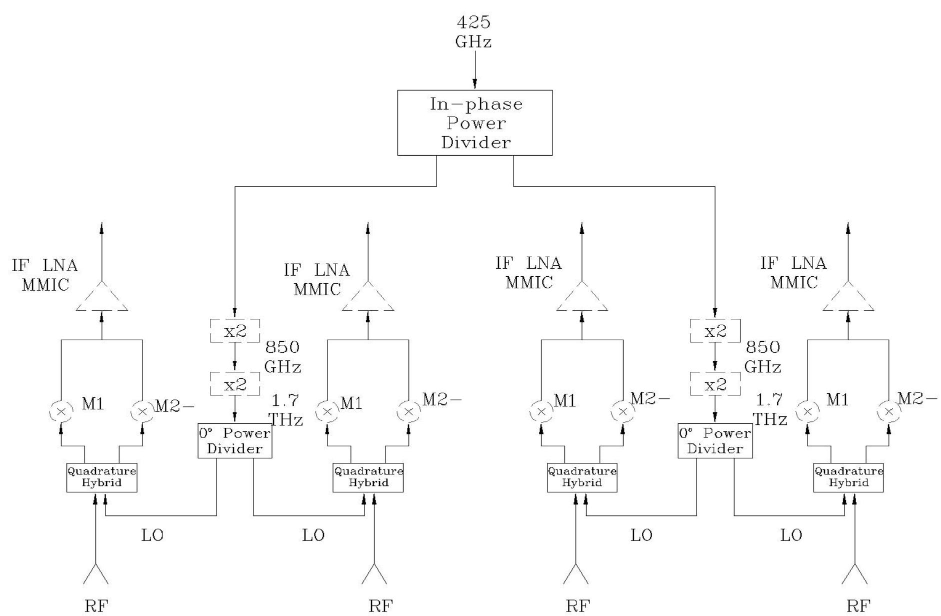

Figure 1. Block Diagram of the Integrated Terahertz Focal Plane Array. All components shown are fabricated and assembled on the split block plane. Components shown within dashed lines are active devices such as diode multipliers, HEB mixers and MMIC IF amplifiers. The rest of the components are passive and are realized in waveguide circuits.

The incoming sky signal in four pixels is fed into four diagonal feedhorns with a separation of 2mm between their centerlines. The separation of 2mm will yield a $2F\lambda$ spacing for a focal ratio of F~ 5.7. With this f-ratio, a nominal length diagonal horn can be coupled into the incoming beam without any input optics. Each diagonal feedhorn transitions into a full-height rectangular waveguide (a=150μm, b=75μm). In each pixel, the RF and LO signals are coupled in through a waveguide hybrid into two HEB mixers to form a balanced mixer arrangement. The combined IF output is fed to a 0 −10 GHz IF amplifier. The SMA outputs of the IF amplifiers and the bias connections for the HEB mixers are brought out at right angle to the split-block plane. The entire array mixer block will measure 1 × 2 × 1 inch in size. The array block will be mounted in a liquid helium cryostat for testing its performance.

INDIVIDUAL SUBSYSTEMS

LO Chain

Rapid progress has been made in producing high-efficiency, wide-bandwidth planar multiplier circuits below 1 THz[5]. These sub-THz devices work mostly using the nonlinear capacitance-voltage (varactor) characteristic of the diode. At frequencies near 2 THz, however, carrier velocity saturation effects seriously limit varactor operation. At these frequencies, very little voltage modulation is possible with the varactor mode[2], leading to very low varactor efficiency. At 2 THz, multipliers can then be operated using the nonlinear resistance-voltage (varistor) characteristic of the device, which requires less voltage amplitude. The multiplier would be expected to work with reasonable efficiency, but varistor operation is always inherently less efficient than varactor operation. Other major challenges for THz LO sources are the shrinking sizes of devices and waveguide circuit features. Recently, a 1.5 THz all-planar solid state LO chain has been demonstrated[3], that also works well at cryogenic temperatures. The next step is to integrate these multiplier designs into the HEB mixer blocks.

Balanced Mixers and Waveguide Hybrids

With our micromilling technique[4], it is possible to construct entire balanced-mixer based receivers completely on waveguide blocks. One common topology of balanced mixers is one in which the signal and the LO are coupled to the individual mixers through a quadrature hybrid (see Figure 2), and the IF's are combined in a 180° hybrid. It is possible to omit the 180° IF hybrid and simply connect the two IF ports in parallel, if the two mixers are biased with opposite polarity[6]. At THz frequencies, the hardest part of realizing a balanced mixer design is the input quadrature hybrid. In waveguide medium, a 3 dB, 90° hybrid can be realized using the so-called branch-line coupler. The branch-line coupler consists of two or more quarter wavelength sections (branches) that bridge across a pair of waveguides, between the broad walls. Figure 2b shows a schematic of the waveguide realization of a branch-line coupler. The figure shows a two-branch section of the branch-line coupler. The heights of the branch lines are the same as the heights (75 μm) of the two main waveguides. We have successfully used endmills of diameter down to 50 μm in multiplier and mixer blocks, and so the branches will not pose a problem. A two-branch coupler however, gives ~10% fractional bandwidth for good input match[7]. Further broadbanding can be accomplished with additional quarter wave sections, with however narrower branch sections. However, a four-branch coupler that covers 20% bandwidth would require mills down to 25 μm diameter, and so is better done by scraping off metal with a very narrow tool. This technique works well for even smaller features.

HEB Mixers and IF Amplifiers

For a diffusion-cooled HEB mixer, the IF bandwidth is independent of temperature. We have chosen Nb diffusion-cooled HEB mixers for our baseline design. Traditionally, the IF output of SIS or HEB mixers is fed through a bias-tee and isolator combination to an IF amplifier that is mounted external to the mixer block, either on a 4K or 12K stage. With a focal-plane array, this will increase the complexity of layout and connectorization inside the dewar. Much better integration and simplicity can be achieved if the IF amplifier is mounted close to the mixer. The block diagram of Figure 1 shows the integration of the IF output of the HEB mixer to InP MMIC low noise amplifiers.

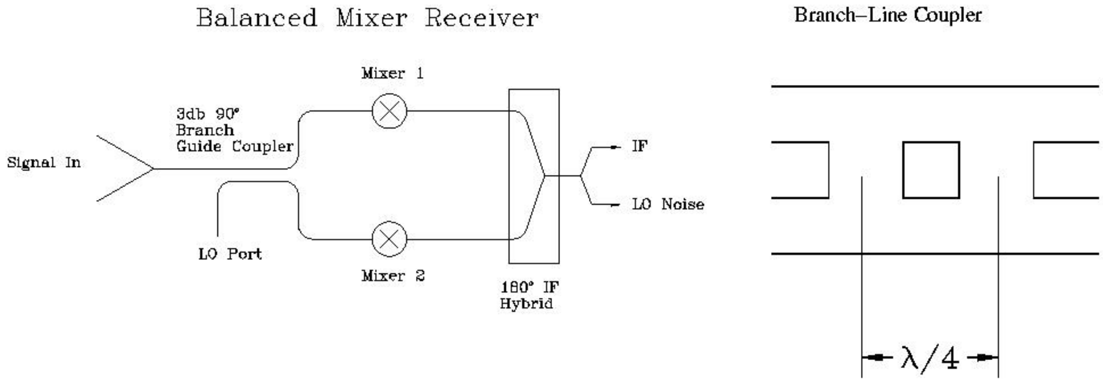

Figure 2. (a) Schematic of a balanced mixer with a quadrature RF hybrid and a180^o IF hybrid. (b) Schematic View of a Waveguide Realization of a branch-line coupler. The view on the E-plane cut, i.e. the split-block view is shown. The separation of the two main waveguides is also approximately a quarter wavelength.

MICRO NC MACHINE

The fabrication of the terahertz array block will be challenging, but achievable because of a novel new method of direct machining of precision waveguide structures on metal blocks that we have developed at the University of Massachusetts. Using this numerically-controlled (NC) machine, many successful high frequency waveguide multiplier circuits and mixer blocks up to 2.5 THz have been fabricated[4]. Machining precision is achieved using a combination of accurate positioners, high-speed pneumatic spindles (running at 70000 rpm), and novel tooling arrangements. Under computer control, the entire waveguide structure of a terahertz multiplier or mixer block can be fabricated to micrometer tolerances in a few hours. With this new micro-milling process, the construction of high performance, low-cost, THz heterodyne mixer arrays, high sensitivity single pixel receivers, LO sources, and bolometer feed-horn assemblies become possible. Micro milling is also ideal for the fabrication of high quality THz quasi-optical components, such as lenses and off-axis reflectors that would form part of a complete THz receiver system.

REFERENCES

1. Wright et al. 1991, "Preliminary spectral observations of the Galaxy with a 7 deg beam by the Cosmic Background Explorer (COBE)" Ap.J., 381, 200.
2. N. Erickson, G. Narayanan, R. M. Grosslein, S. Martin, I. Mehdi, P. Smith, M. Coulomb, G. DeMartinez, 2001, "Monolithic THz Frequency Multipliers", Proceedings of the Twelfth Int'l Symp. on Space THz Technology, San Diego, CA.
3. N. Erickson, G. Narayanan, R. M. Grosslein, A. Maestrini, E. Schlecht, G. Chattopadhyay, J. Gill, I. Mehdi, 2002, "1.5 THz all-Planar Multiplied Source", to appear in the Proceedings of the Thirteenth Int'l Symp. on Space THz Technology, Harvard, MA.
4. G. Narayanan, N. Erickson, R. Grosslein, "Low Cost Direct Machining of Terahertz waveguide Structures," Tenth International Symposium on Space Terahertz Technology, pp. 518-528, Mar. 99.
5. N. R. Erickson, G. Narayanan, R. P. Smith, S. C. Martin, I Mehdi, T. W. Crowe, and W. L. Bishop, 2000, "Planar Frequency Doublers and Triplers for FIRST", Proc. of the Eleventh Int'l Symp on Space THz Tech., pp 543-551, May 2000.
6. A. R. Kerr, S-K. Pan, N. Horner, J. E. Effland, K. Grady, and A. W. Lichtenberger, 2000, "A Single-Chip Balanced SIS Mixer for 200-300 GHz", Proc. of the 11th Int'l Symp. on Space THz Tech., Ann Arbor, May 2000.
7. G. Matthaei, L. Young, and E. M. T. Jones, "Microwave Filters, Impedance-Matching Networks, and Coupling Structures", Artech House, Inc. 1985, pp. 809-842.